# B Mode Polarization

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# *Gravity waves*

- Expanding Universe + Uncertainty principle → Metric perturbations → Gravity waves.
- Inflation predicts gravity wave amplitude $\propto (H/m_{pl})^2 = V/3m_{pl}^4 = (E_{inf}/m_{pl})^4$.
- $C_\ell^{TT}(\text{tensor}) \propto (E_{inf}/m_{pl})^4$
- Gravity waves → Polarization during recombination and reionization. Both E and B modes of polarization are produced.
- Scalar perturbations only produce E mode polarization.
  (Kamionkowski, Kosowsky and Stebbins 1997,
  Seljak and Zaldarriaga 1997)

# *B mode polarization*

- E and B are rotationally invariant quantities constructed out of $Q = (I_{xx}-I_{yy})/4$ and $U=I_{xy}/4$.

- Flat sky: $Q(\mathbf{n}) \pm i\, U(\mathbf{n}) =$
$$- (2\pi)^{-2} \int d^2\boldsymbol{\ell}\ \ [E(\boldsymbol{\ell}) \pm i\, B(\boldsymbol{\ell})]\ \ \exp(\pm 2\, i\, \phi_{\ell})\ \ \exp(i\, \boldsymbol{\ell}.\mathbf{n})$$

- Parity dictates that $\langle EB \rangle = 0 = \langle TB \rangle$

  (Kamionkowski, Kosowsky & Stebbins 1997, Zaldarriaga and Seljak 1997.)

- Higher order (in perturbation) processes like lensing can create "scalar" B mode polarization.

- Foregrounds: lensing, secondary sources of polarization like kSZ, polarized point sources.

# WMAP Constraints on $\mathcal{E}_{inf}$

WMAP result for the scalar amplitude:

$$\Delta^2_{\mathcal{R}}(k_0) \simeq 2 \times 10^{-9}$$

$$\frac{E_{\rm inf}}{\rm m_{GUT}} \simeq 3\,\epsilon(k_0)^{1/4}$$

WMAP result for the tensor amplitude:

$$r(k_0) < 1$$

$$\epsilon(k_0) < 0.06$$

$$\epsilon \equiv {\rm m}^2_{\rm pl}(V'/V)^2/2$$

$$k_0 = 0.002/{\rm Mpc}$$

$$E_{\rm inf} < 1.5{\rm m_{GUT}} = 3 \times 10^{16}\,{\rm GeV}$$

# *Detectability of primordial GW*

- B mode signal is contaminated by gravitational lensing of the CMB by large scale structure which converts some of the (much larger) E mode polarization into B.

- The residual scalar B mode limits the detectability (at $3\sigma$) of tensor B modes to $r > 10^{-5}$ which implies $E_{inf} > 2 \times 10^{15}$ GeV.

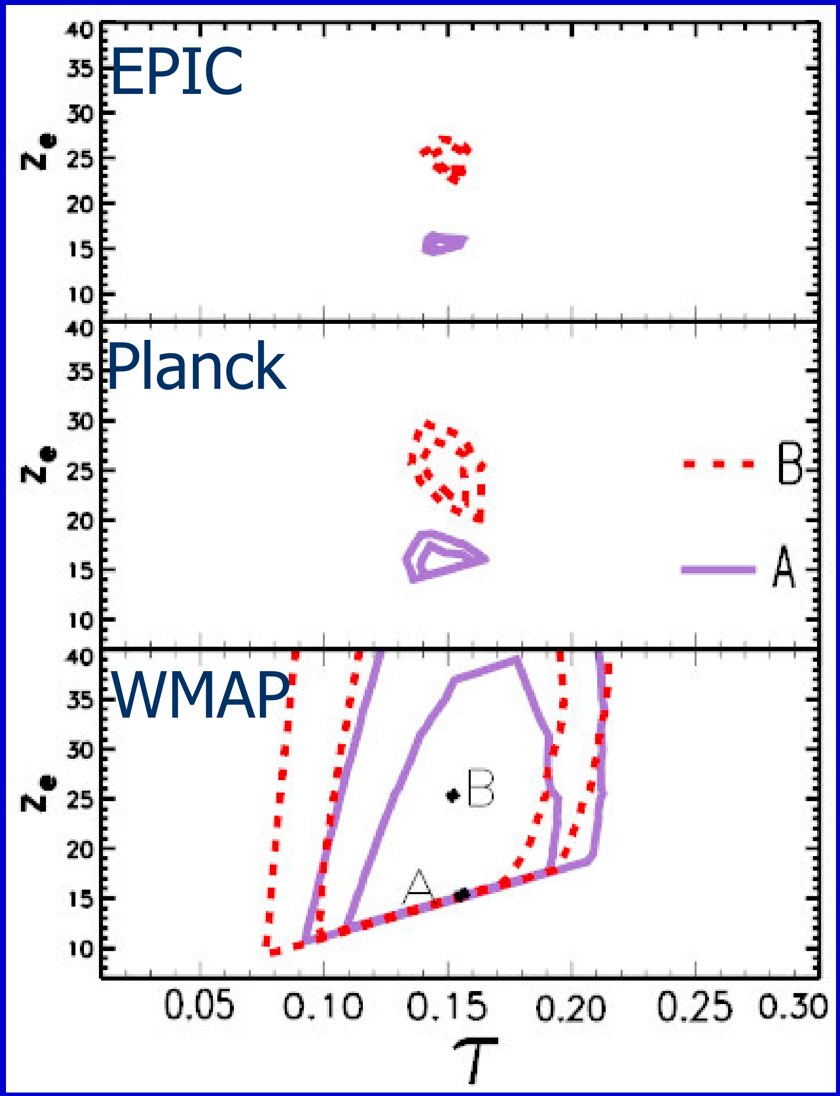
Knox and Song, 2002

Kesden, Cooray and Kamionkowski, 2002

Kaplinghat, Knox and Song, 2003

# *Large Angle CMB Pol*

- Large angle B mode signal can be used to measure the primordial GW amplitude (not contaminated by lensing).
  - Min($E_{inf}$) scales as $1/\tau^{1/4}$.
- Large angle CMB polarization can map out the reionization history.
- Indirect measurement of the primordial scalar power spectrum amplitude.



# *Detectability of primordial GW*

- Optimism?
- Yes. GUT scale ($10^{16}$ GeV) is special (unification of forces). Also successful inflation at smaller $E_{inf}$ requires flatter potentials.

- But aren't we already probing GUT scales?
- Yes. But GUT scale physics does not have to lead to a potential whose amplitude is exactly $m_{GUT}^4$.

- What if SUSY (or some other extension) is discovered at LHC?
- Doesn't change the unification motivation.

- Could there be later periods of inflation which overwhelm GUT scale inflation?
- Yes. Last one wins <u>if</u> it lasts long enough.

# *Detectability of primordial GW*

- Slow roll implies (Lyth, PRL 1997)

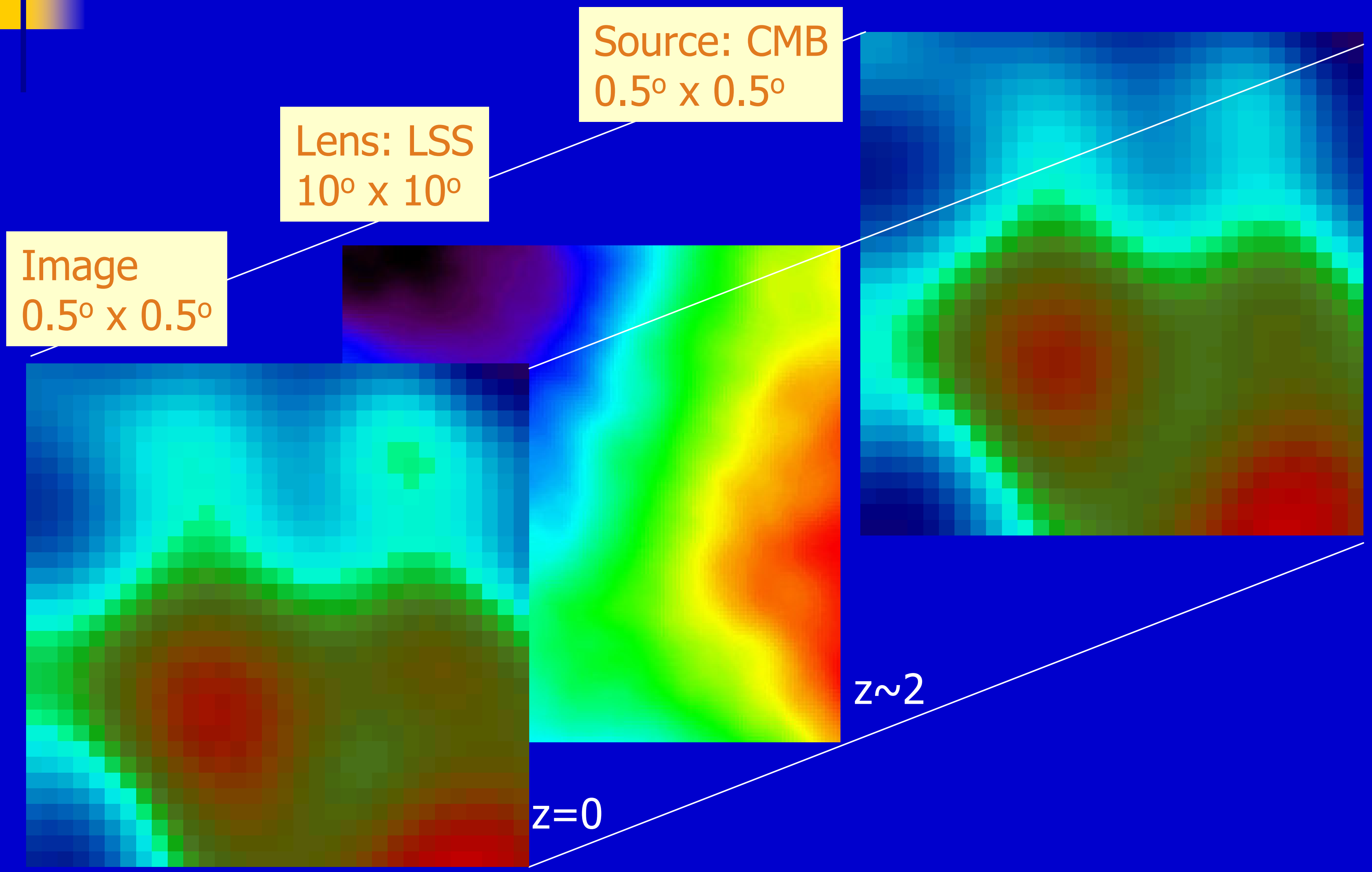
$$\frac{\Delta\phi}{m_{pl}} \simeq \sqrt{2\epsilon}\Delta N$$

- For detectable B modes $\Delta\phi > 10^{-3}\,\Delta N\, m_{pl}$. Effective field theory description valid.

- Interpretation of WMAP Monte Carlo study of slow roll inflationary models. For $0 < \eta < 3\varepsilon$, unless $1-n_S < \sim 10^{-4}$, GW is at a detectable level. For $\eta > 3\varepsilon$ or $\eta < 0$, it is possible that GW is at a detectable level.

$$\eta \equiv m_{pl}^2 \frac{V''}{V}$$

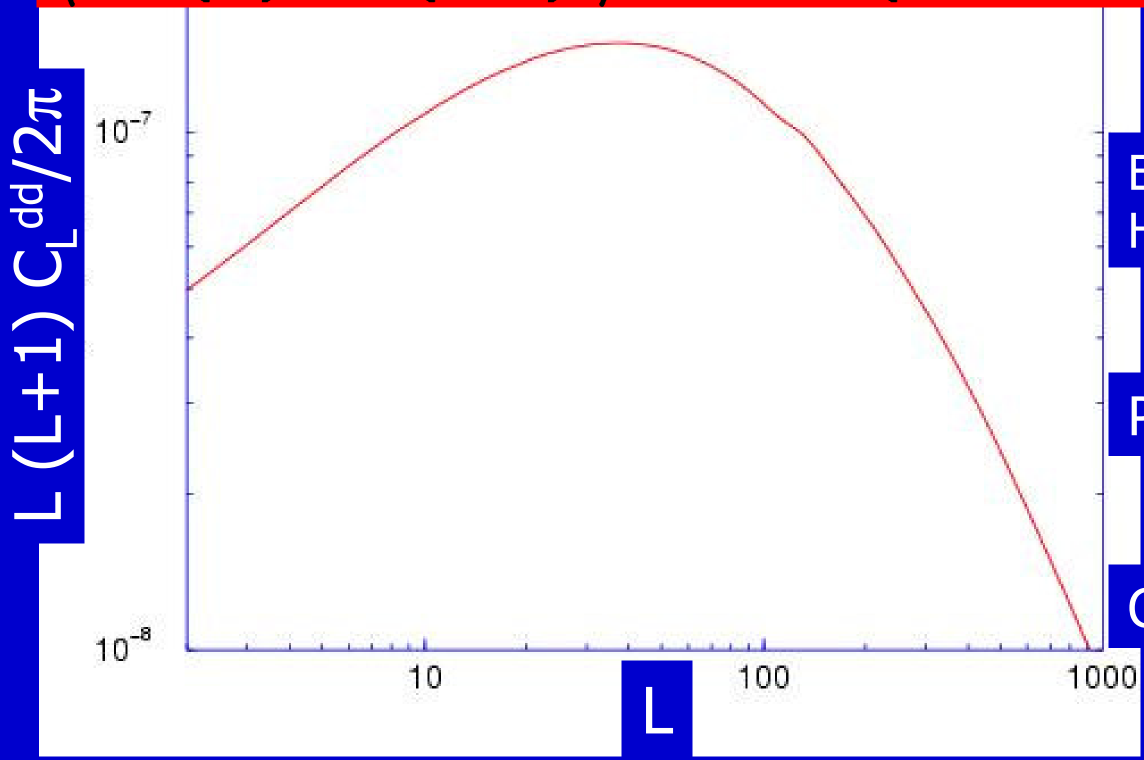
# *Lensing of the CMB*



# *Coherence of (CMB) Lensing Deflection*

$$T(\vec{n}) = \tilde{T}(\vec{n} + \vec{d})$$

$$\langle T(\vec{l})T(\vec{l}\,')\rangle \propto \vec{d}(\vec{l} - \vec{l}')$$




Estimate **d** from CMB maps
Hu and Okamoto, 2002

Peak sensitivity ~ z=2

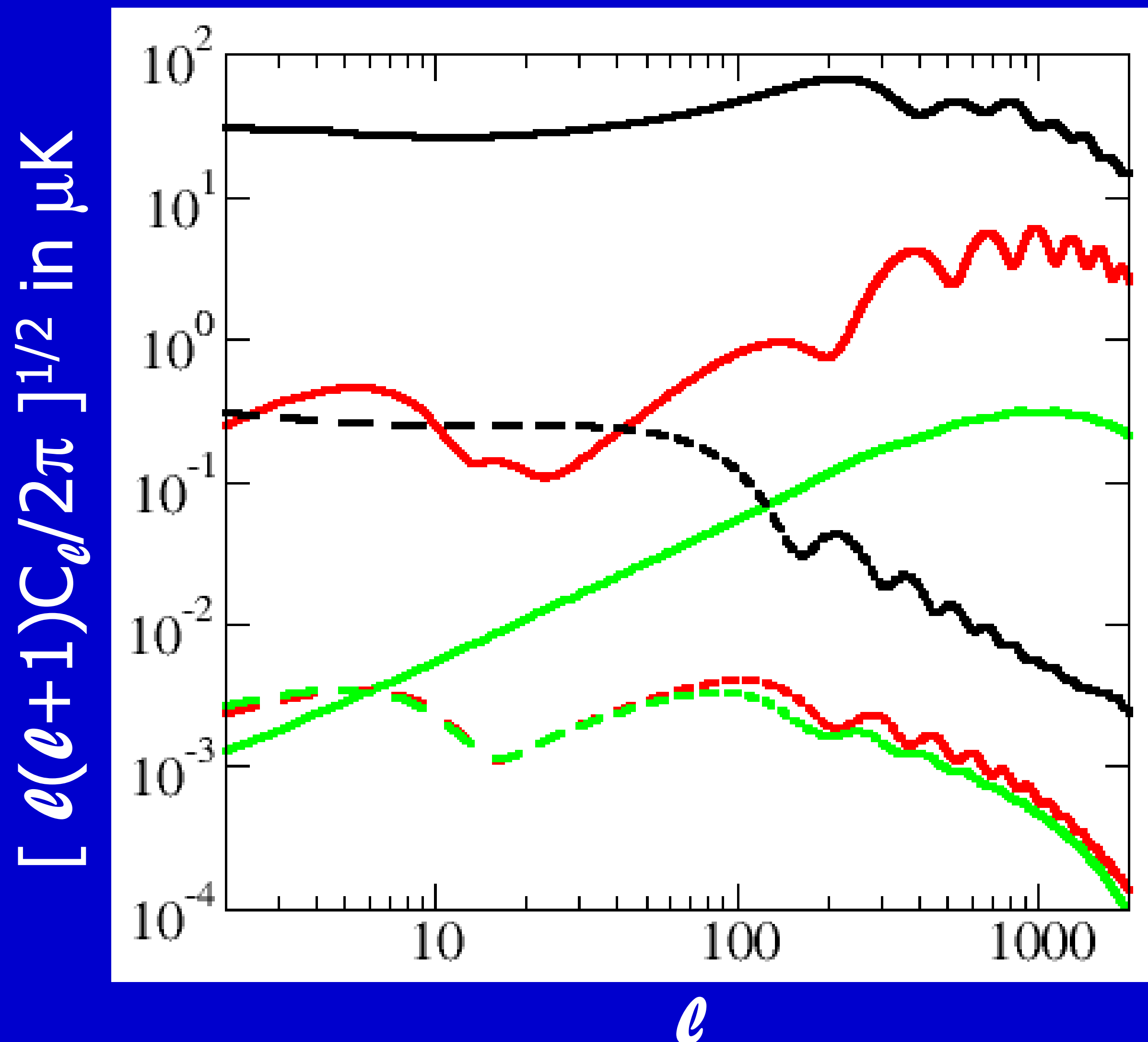
Coherence ~ 10 deg

# *Spectra*

Black: TT
Red: EE
Green: BB

Solid: Scalar
Broken: Tensor

T/S = $10^{-4}$



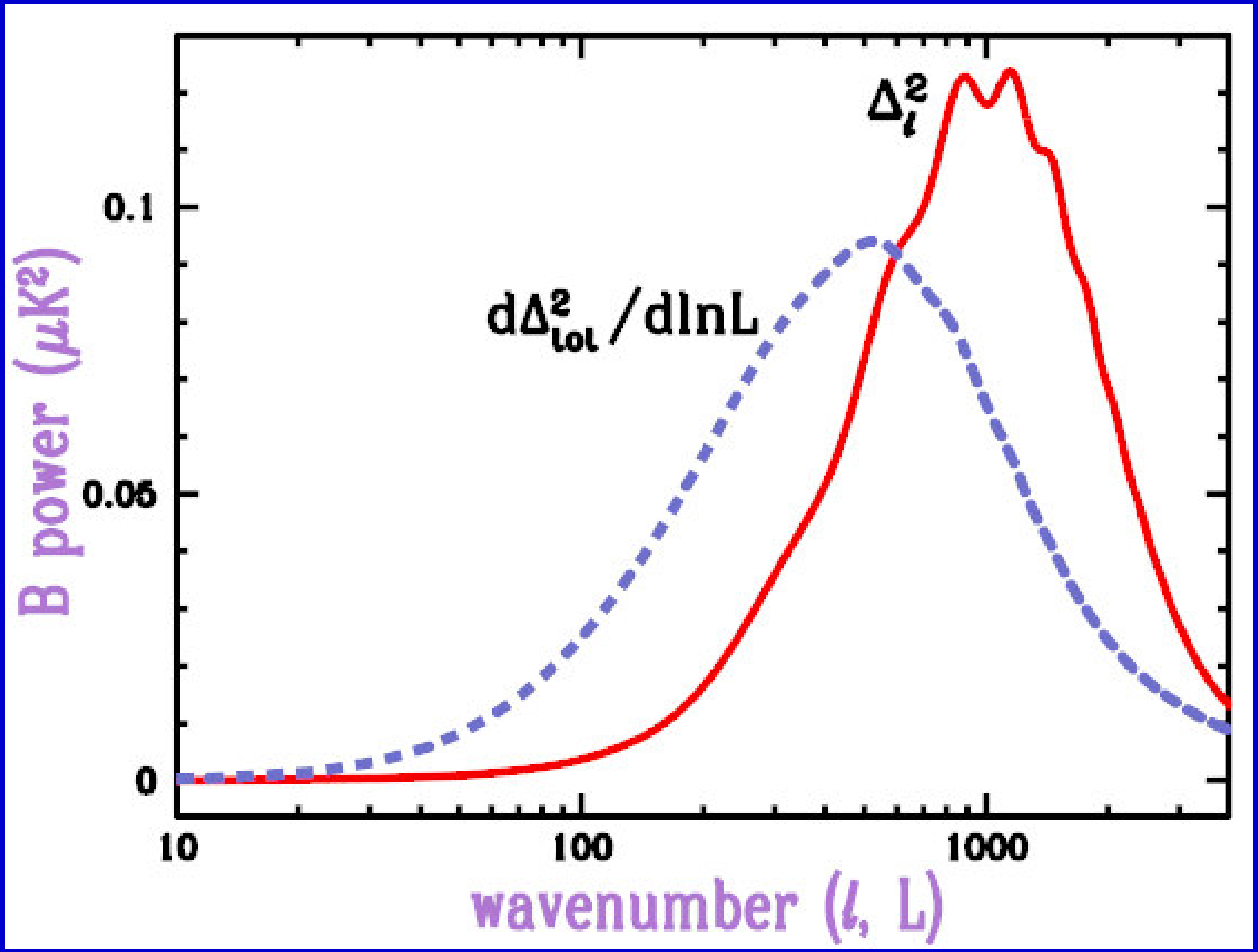
## *Lensed BB power spectrum*

$$C_l^{BB} = \int d^2L \, C_{|\vec{l}-\vec{L}|}^{\tilde{E}\tilde{E}} \, C_L^{dd} \, W^2(\vec{L},\vec{l})$$

$$\Delta_l^2 \equiv \int_{\vec{l}\in B} \frac{d^2l}{(2\pi)^2} C_l^{BB}$$

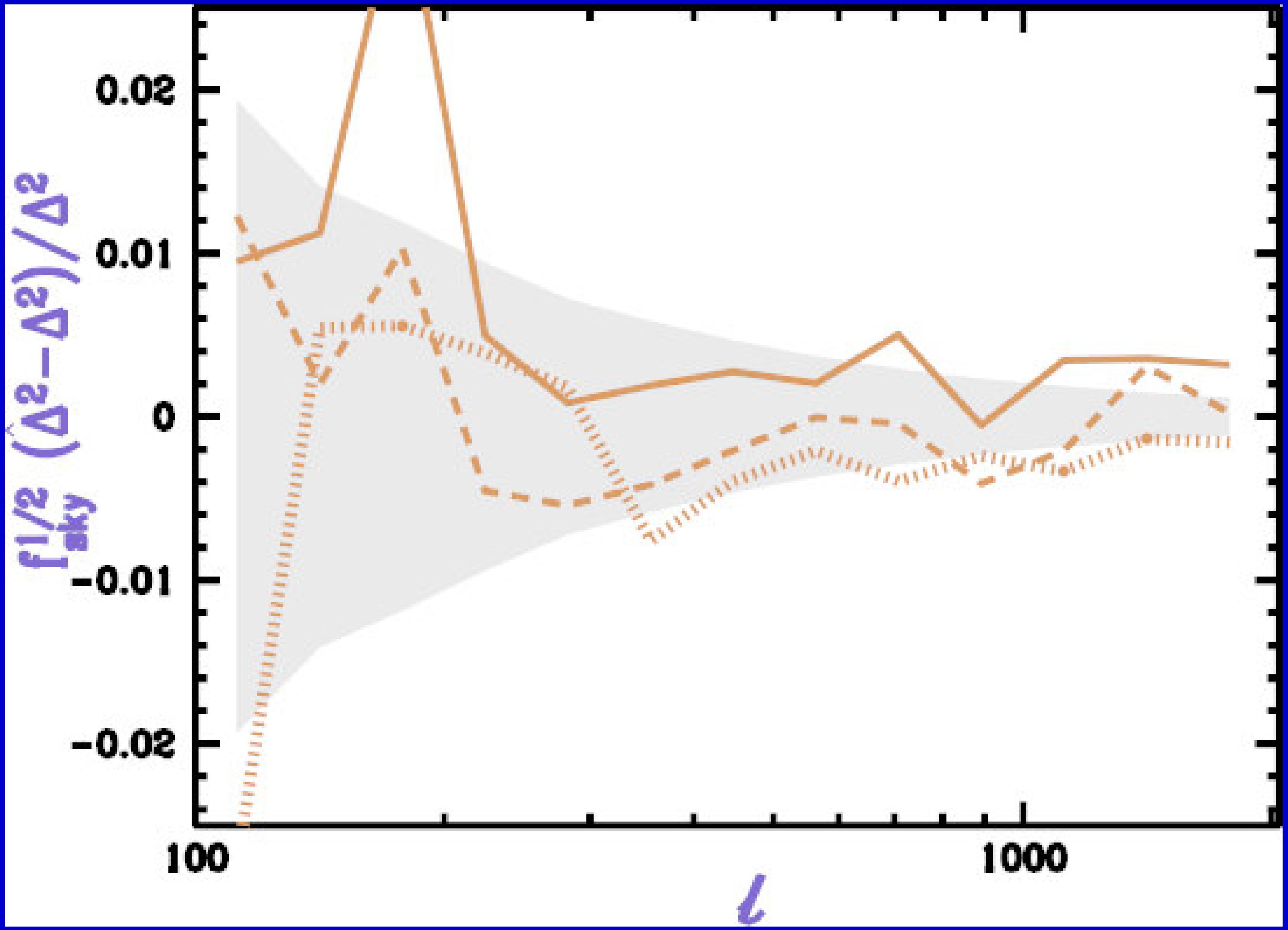
$$\Delta_{\mathrm{tot}}^2 = \int \frac{d^2l}{(2\pi)^2} C_l^{BB} = (0.46\mu\mathrm{K}/T)^2$$

# *Lensed BB power spectrum*




Smith, Hu, Kaplinghat astro-ph/0402442

# *Measuring B power: Cosmic Variance*

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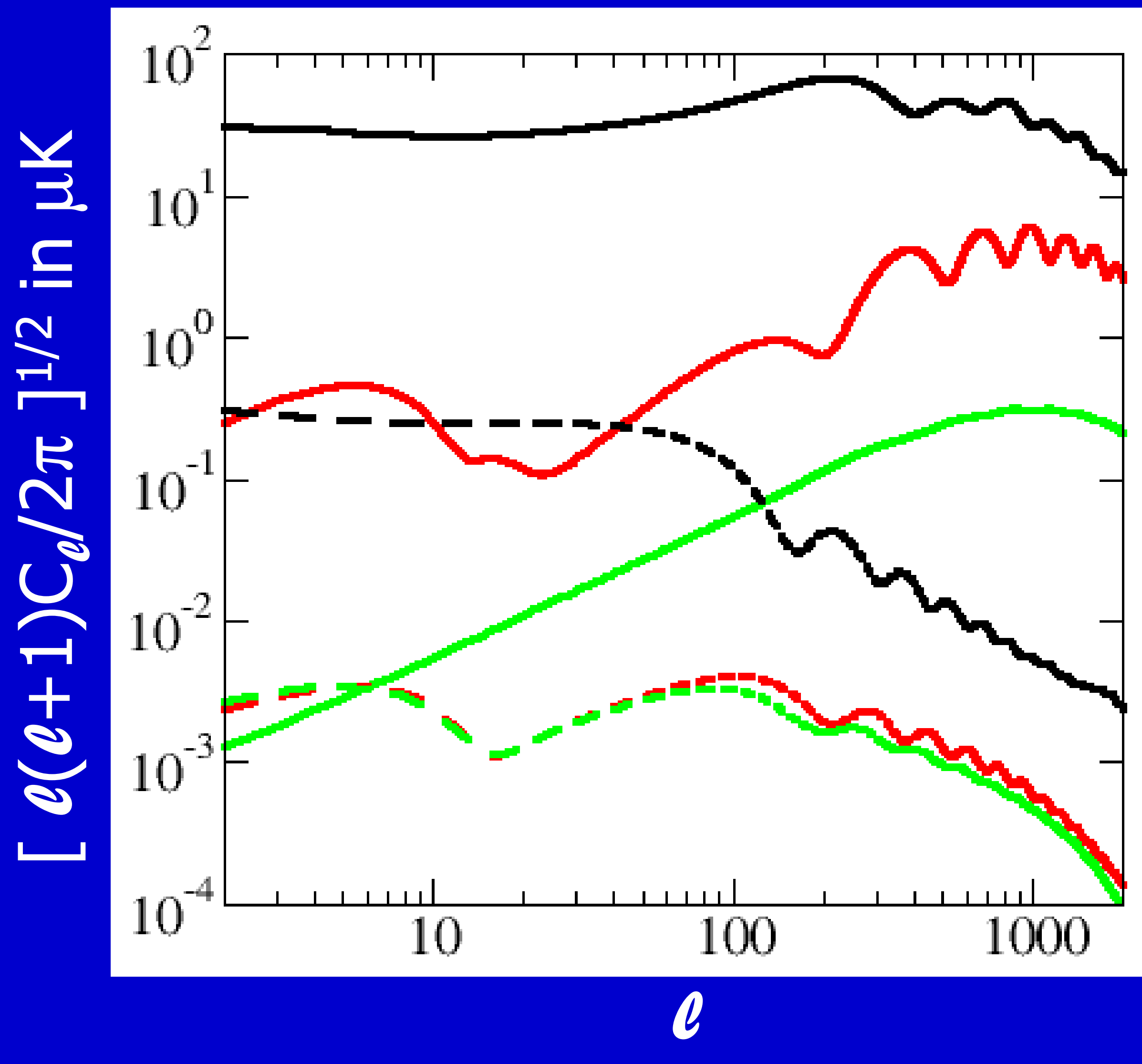


# Secondary Science Goals

- Secondary science goals: inflationary potential parameters, amplitude of scalar perturbations, neutrino mass, recombination physics, matter budget to high precision, angle subtended by sound horizon to third decimal place.

- To clean the scalar (lensed) B mode signal one would need to go down to about 5 arcmin resolution (perhaps lower). Secondary science goals listed above (and perhaps others) would then come for free. No need to optimize the experiment for secondary science goals.

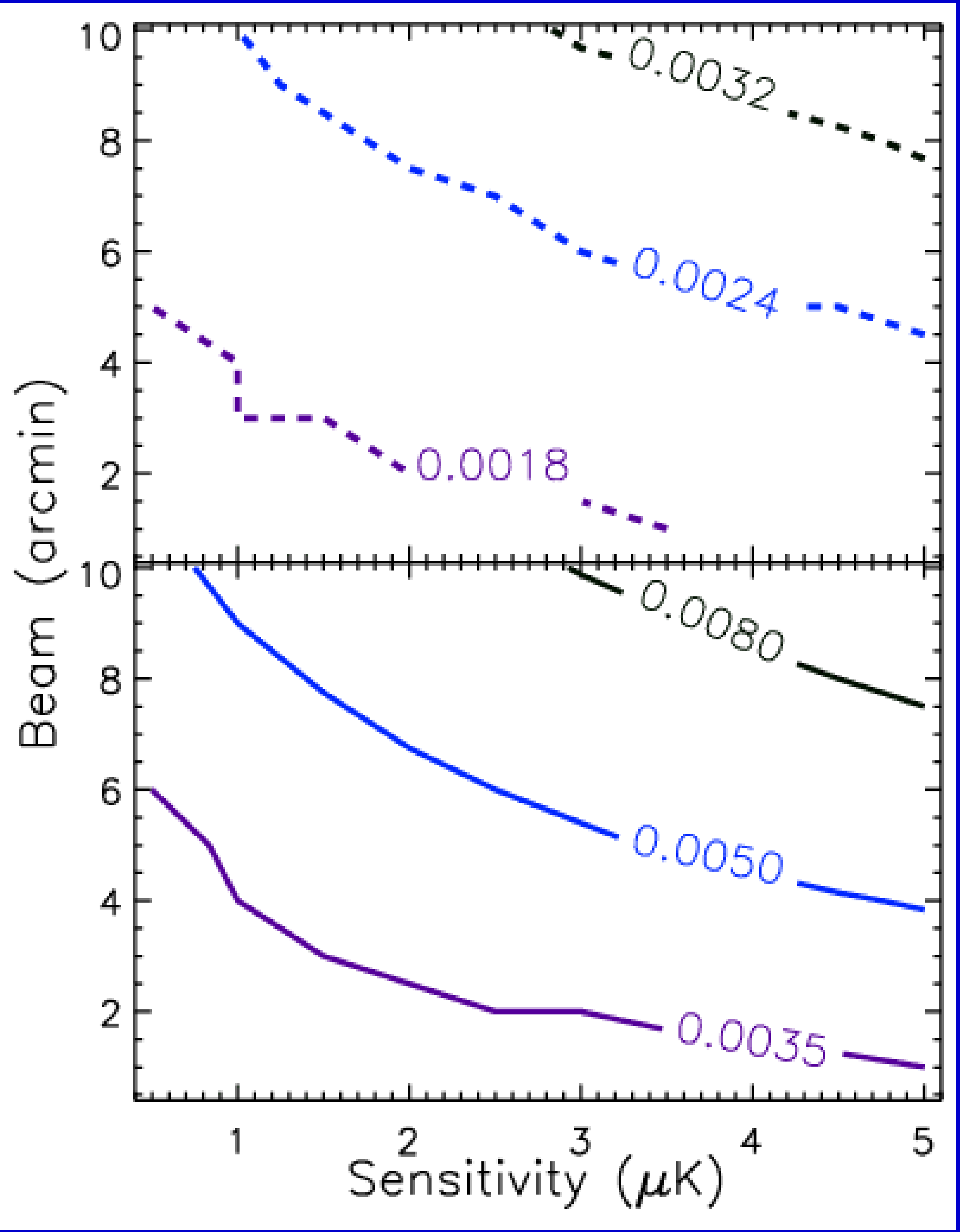
- Could build an experiment sensitive only to the large angle signal for measuring primordial B modes. Is this wise?

# Inflation

Top panel: $\sigma(n')$
Contours at 0.0018, 0.0024 and 0.0032
($\sqrt{\sigma(n')}$ = 0.056, 0.049, 0.042)

Bottom panel: $\sigma(n)$
Contours at 0.0035, 0.005 and 0.008

Typical inflationary models have
$n' \sim (n-1)^2$

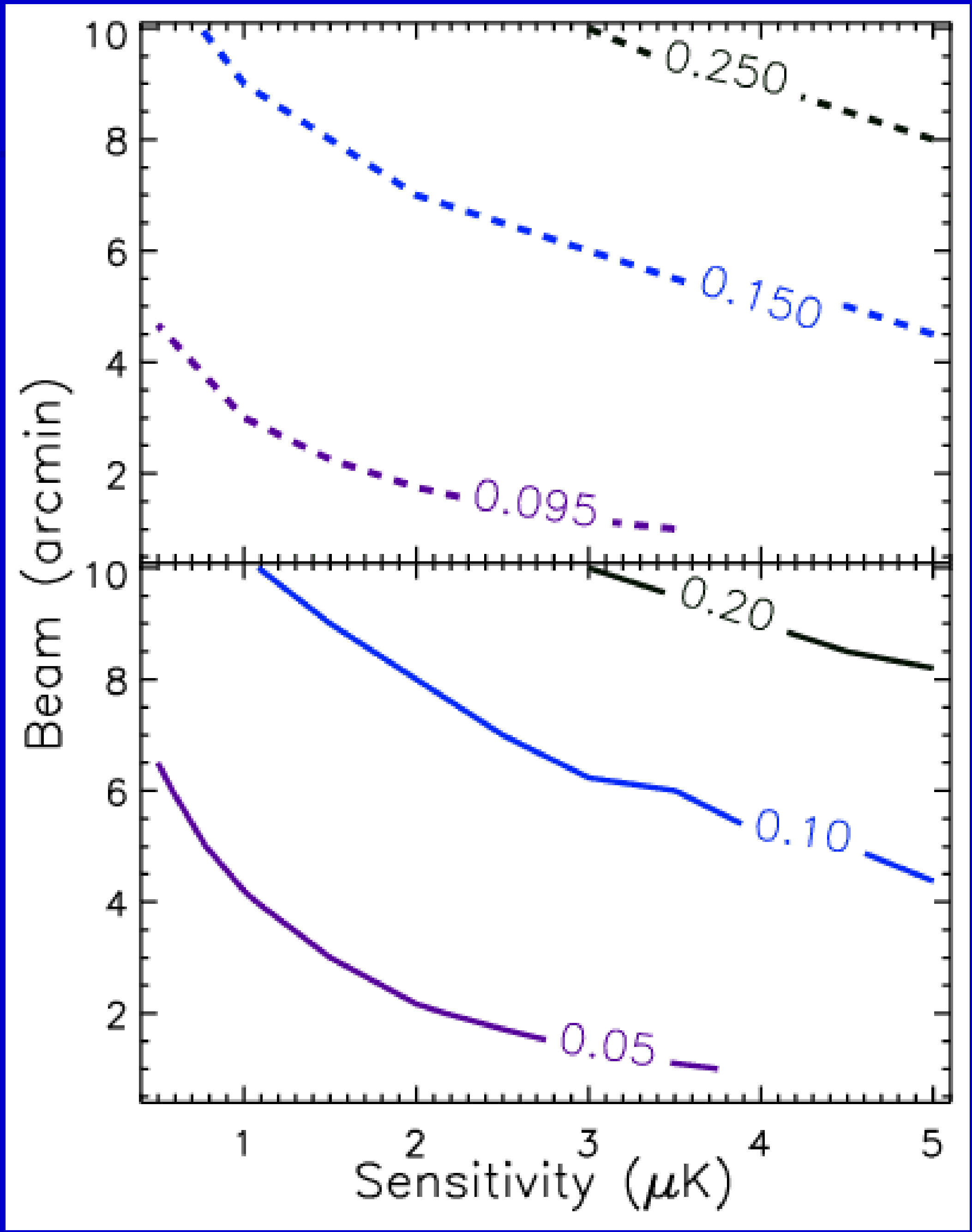


# *Neutrino*

Top panel: $\sigma(N_\nu)$
Contours at 0.095, 0.15 and 0.25

Bottom panel: $\sigma(m_\nu)$
Contours at 0.05 eV, 0.1 eV and 0.2 eV

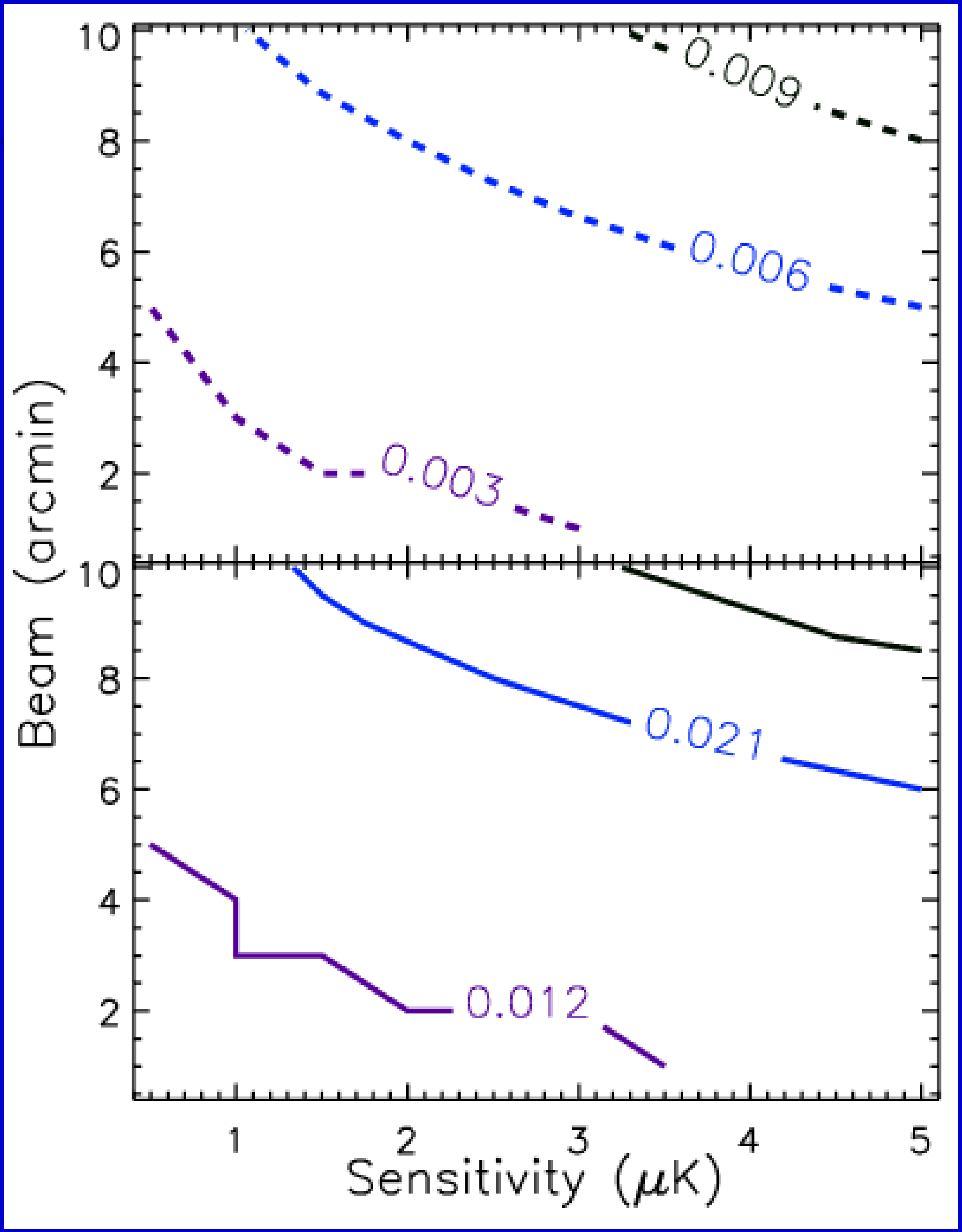
0.05 eV < Sum of active neutrino masses < 1 eV



# *Matter Budget*

Top panel: $\sigma(w_B)/w_B$
Contours at 0.3%, 0.6% and 0.9%

Bottom panel: $\sigma(w_M)/w_M$
Contours at 1.2%, 2.1% and 3%



# *Consistency Checks*

- Determining $\omega_B$, $Y_P$ and $N_\nu$ to high precision will facilitate precision consistency tests between CMB and BBN.
- Given $\omega_B$, a measurement of $Y_P$ from the CMB can be translated into a measurement of $N_\nu$ at BBN such that $\sigma(N_\nu) = \sigma(Y_P)/0.013$ which for EPIC translates to $\sigma(N_\nu) \approx 0.4$.
- We can independently measure $N_\nu$ from the CMB. With EPIC it might be possible to go down to $\sigma(N_\nu)$=0.1.
- Test of recombination physics.

# *Lensing potential estimator*

$$\phi(\vec{L}) = \int d^2\ell X(\vec{\ell})Y(\vec{L}-\vec{\ell})W(\vec{\ell},\vec{L})$$

Hu and Okamoto, 2002

- Optimize in the presence of foregrounds.
- Reduce sensitivity to small scale signal. This will increase noise which is preferable to biasing the estimator.
- EB estimator naturally suited for this.

# Foregrounds

- "Doppler": Due to bulk motion of clustered environments. Vishniac, kSZ and patchy reionization effects.
- Second order effect. Expand visibility function to second order in baryon density or ionization fraction.
- Patchy reionization effects model dependent.
- kSZ and patchy reionization peak on smaller scales.

S & Z, MNRAS, 1980
Vishniac, ApJ 1987
Hu & White, A&A 1996
Hu, astro-ph/9907103

# *Foregrounds: polarization*

- Secondary processes (being intrinsically non-gaussian) produce both E and B modes. All this requires is a quadrupole in temperature after reionization which is of course present. The magnitude and shape can be calculated for Vishniac effect. Patchy reionization signal is more model dependent but peaks at smaller angular scales.

- This might be the limiting factor (and not lensing) for detection of GW if $T/S < 10^{-4}$.

- "Non-doppler" foregrounds. Dusty galaxies and radio point sources.

# *Sensitivity to foregrounds*